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Directions for Advanced Use of Nuclear Power in Century XXI

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ABSTRACT

Nuclear power can provide a significant contribution to electricity generation and meet other needs of the world and the U.S. during the next century provided that certain directions are taken to achieve its public acceptance. These directions include formulation of projections of population, energy consumption, and energy resources over a responsible period of time. These projections will allow assessment of cumulative effects on the environment and on fixed resources. Use of fossil energy resources in a century of growing demand for energy must be considered in the context of long-term environmental damage and resource depletion. Although some question the validity of these consequences, they can be mitigated by use of advanced fast reactor technology. It must be demonstrated that nuclear power technology is safe, resistant to material diversion for weapon use, and economical. An unbiased examination of all the issues related to energy use, especially of electricity, is an essential direction to take.

I. INTRODUCTION

To achieve the vast rewards of nuclear power during the next century, a new perception of nuclear technology is needed, both on the part of the world public as well as on the part of nuclear technologists and entrepreneurs. A significant contribution by nuclear technology to the generation of electricity throughout the world is dependent on this new perception, which in turn is dependent on adherence to a new ethical ideology. The code of ethics that must be in place would make today's world population responsible for beneficial consideration of the populations that will inhabit the world far in the future. The actions of today's population, while not required to be sacrificial, must be such as to allow future populations adequate options for pursuit of their happiness. Practically, "far in the future" is not endless. We cannot presume to correctly predict future world conditions, and the validity of any presumption diminishes as the future period is extended. Although it is difficult to quantify what the extent of our concern should be, it is clearly more than a century but probably not over a millennium. Below we examine the directions that need to be taken to realize, in a responsible manner, the maximum advantage of nuclear power in Century XXI.

II. DIRECTIONS TO TAKE

For nuclear power to be broadly implemented in the next century, nuclear technologists and entrepreneurs must achieve success in convincing the public of the superiority of nuclear-generated electricity in meeting all the objectives important to the world population. For the public to be convinced, of course, the advantages must be demonstrated to be irrefutable, and the disadvantages acknowledged and reconciled. The compelling advantages of nuclear power can be demonstrated by exerting diligent efforts along several directions to: (1) maintain long-term projections of energy needs, (2) maximize energy resource utilization, (3) minimize adverse environmental effects, (4) achieve a high level of safety, (5) minimize the risk of nuclear material diversion for weapon use, (6) minimize power cost by appropriate system design, and (7) broaden the applications of nuclear power technology. Technologists must continually share information with the public on progress along these directions. Unbiased examination of all pertinent issues and objective comparative analyses of all reasonable options for generation of electricity, together with a non-righteous public information program will be essential for gaining public acceptance of nuclear power. We examine these directions below and then propose actions that need to be taken to achieve significant implementation of nuclear power.

A. Energy Projections

Reasonable long-term projections of energy demand and energy resources are needed. These projections must be made on the basis of U.S. population needs as well as on those of the world. The former is clearly in the national interest of the U.S. and, although not as obvious, the latter is as well. (We have seen how closely the U.S. economy is coupled to the economy of other countries. These economies are, in turn, closely coupled with energy supply and demand). Based on demand projections, an assessment must be made of the durability of energy resources. Practically complete and efficient utilization of energy resources will extend their durability. It must be understood, however, that these projections are not forecasts, but rather projections based on a large number of assumptions. Continual review of these projections and their assumptions is required. The Energy Information Administration (EIA) performs such projections over a limited (~20-year) time scale. Certainly, this work needs to be continued, and the projections extended over a 100-year period.

Energy demand, and electricity needs in particular, can be expected to grow with increased population. The historical population in 1998 and population projections by country for the years 2025 and 2050 by the Department of Commerce have been published.[1] By continuing the growth trends indicated in the latter data for the world and for the U.S. in an approximate manner, we arrive at the *uninformed* population projections during the next century as shown in Table 1.

Population values for 2000 were interpolated from the data[1] for 1998 and 2025. Values beyond 2050 are estimated here on the basis of the earlier trends. The extrapolated values in Table 1 for the years 2075 and 2100 represent 13% and 8% increases over the previous quarter century, respectively, for the world and 10% and 5% increases over the previous quarter century, respectively, for the U.S. These increases are substantially lower than the increases of 31% and 24% projected by the Department of Commerce for the world and the U.S., respectively, in the first quarter century. The intent here is to apply reasonably lower rates in order not to exaggerate energy resource deficits that can be expected to result from continued rapid population growth.

Table 1. Population (millions) projections to the end of the century.

	2000	2025	2050	2075	2100
World	6055	7923	9346	10600	11400
U.S.	270	335	394	440	472

The world primary energy use for a "middle course" scenario is projected to increase by a factor of 3.8 during the next century.[2] The published projected values[2] for 2050 and 2100, and interpolated values for 2025 and 2075 are shown in Table 2. The EIA has projected values[3,4] for the world and the U.S. only to 2020. Projections of the annual primary energy use in the U.S. beyond 2020 in Table 2 are based on the same growth rate as that projected for the U.S. population as shown in Table 1. On this basis, primary energy use in the U.S. will increase by a factor of 1.7 during the next century. The reader should recognize that the projected values of primary energy use beyond 2020 for the U.S. are *uninformed*. The projections, nevertheless, seem reasonable and provide for continuity in the present discussion.

Table 2. Total annual primary energy (TWy) use projections to the end of the century.

	2000	2025	2050	2075	2100
World	13	21	28	37	49
U.S.	3.3	4.1	4.8	5.2	5.5

Throughout the period 2000-2020, EIA projects that electricity use will require a 36% share of the total primary energy use in the U.S.[3] Throughout the same period, EIA projects that electricity generation will require a 38% share of the total primary energy use in the world.[4] However, electricity generation could represent a larger share of the total primary energy use in the future. This expectation results from the increasing probability of greater application of electricity in the transportation sector to mitigate environmental effects; expected future sanitary water shortages may well require increased use of electric power for water purification or sea water desalination; and proliferation of new-technology equipment requiring electricity. Additionally, with more than half the world population in developing countries, a greater share of primary energy for electricity will be required on a world basis.

Projected annual net electricity use during the next century is shown in Table 3. Data from both EIA and World Energy Conference (WEC) were used to develop Table 3. Values not explicitly available in these references[2,3,4] were derived on the basis of the values in Table 2, the "early century" primary share for electricity, and a generation efficiency of 0.33 (inferred efficiency[4] for electric generation in the world in 2020).

Table 3. Annual net electricity (TWy) use projections to the end of the century.

	2000	2025	2050	2075	2100
World	1.54	2.53	3.57	4.64	6.14
U.S.	0.38	0.48	0.56	0.61	0.64

B. Resource Utilization

A number of assessments of natural energy resources, both on global and country levels, have been performed. These assessments are difficult to make at best, and more difficult on which to base energy decisions. There does not appear to be general agreement on how long these resources will last. Some point to the fact that remaining reserve/production ratios of oil and gas for the last 50 years have been relatively stable or have actually increased.[2] This being true, it is difficult to postulate that these resources are running out. Nevertheless it is useful to consider the quantity of resources believed to be eventually available in the context of the energy projected to be used during the next century and beyond. Table 4 shows the estimated world fossil fuel resources[2] available.

Table 4. Estimated resource base (TWy) for oil, gas, and coal.

	Conventional	Unconventional	Conv.+Unconv.
coal	4760	0	4760
oil	413	735	1148
gas	588	630	1218
total	5761	1365	7124

The cumulative primary energy projected to be used by the world during the next century, based on Table 2 projections, is 2900 TWy. At this rate of consumption, oil and gas can not be expected to last through the next century without extensive use of coal. A more detailed view of the longevity of these resources is indicated in Table 5. Cases are presented for utilization of conventional resources only and for utilization of both conventional and unconventional resources under the assumption that only one resource is used, two resources (oil and gas) are used, or all three resources (coal, oil, and gas) are used. The highest longevity, year 2186, results if all these resources, both conventional and unconventional are used to meet the projected primary energy demand. The analysis used assumes no growth in energy demand after 2100. On the other hand, it does not take into account the increase in longevity from use of non-fossil fuel resources, such as nuclear, hydroelectric, geothermal, and the potential solar and wind power contributions.

Table 5. Estimated longevity (year of exhaustion) of world oil, gas, and coal resources.

	coal	oil	gas
conventional resources			
only one	2138	2024	2032
only oil/gas		2049	2049
coal/oil/gas	2158	2158	2158
conventional + unconventional resources			
only one	2138	2054	2057
only oil/gas		2088	2088
coal/oil/gas	2186	2186	2186

Current assessments of uranium resources indicate that, with the appropriate fuel cycle, already-mined-uranium could power fast reactors for centuries. At the end of 1995 over one million tonnes of depleted uranium was in storage[5]. This amount translates to over 3000 TWy of primary energy for electricity generation in the appropriate fast reactor system with fuel recycling, or about 1000 TWy of net electricity. Thus, depleted uranium could be used to meet the total world demand for electricity until the year 2200, assuming the projected electricity demand indicated in Table 3 during the next century and a steady demand (at the year 2100 rate) throughout the next century. In addition to the depleted uranium inventory, there is a large amount of uranium in spent fuel. At the end of 1997 this amount is estimated to be equivalent to 500 TWy of primary energy for electricity generation.

The longevity of uranium could be further extended by using newly mined uranium. Reasonably assured resources of uranium in the world at the beginning of 1997 is over 3 million tonnes.[6] Properly used, newly mined uranium could meet the total world electricity demand for over 4.5 centuries at the year 2100 rate. Thus the combined longevity of depleted uranium, uranium in spent fuel, and uranium in the mine approaches seven centuries if used exclusively for electricity generation. Use of renewable resources to meet electricity demand would extend the longevity of uranium over a millennium.

C. Environmental Impact

The environmental impact of nuclear power plants is substantially more benign than from fossil power plants, but this needs to be quantified and made clear to the public. Solar and wind power plants are attractive from an environmental point of view. Development of the latter should be pursued in the context of satisfying continuous power demands. This requires, however, energy storage systems for periods when the sun doesn't shine or the wind doesn't blow. Alternatively, a standby gas fueled plant might be pressed into service during such periods. The cost analyses of renewable systems must take into account the need, fuel availability, environmental effects, and cost, for supplementary power during these periods. Comparative assessments of the environmental effects from candidate power options must examine their complete infrastructure to allow a true quantification of their impacts.

Global warming may be confirmed to be a real threat in the future. If the Kyoto protocols are to be followed, requiring a return to 1990 levels of carbon release to the atmosphere (or lower), severe curtailment of the use of fossil fuels will be required. We examine some bounding scenarios below from the standpoint of the electricity sector. It is clear that other sectors of energy use, for example transportation, would have a more difficult time in cutting back on carbon emission than the electricity sector. The electricity sector might thus need to increase its relative share of the primary energy use projected in Table 2, and therefore require that an even greater share of the electricity be produced by combined nuclear and renewable resources.

In 1990, U.S. power plants produced 477 TgC (teragrams of carbon in carbon dioxide) from generation of 320 GWe. Coal plants produced 56% of the electricity and 86% of the carbon emissions. In 1990, world power plants produced an estimated[4] 1832 TgC from generation of 1190 GWe. The approximate generation shares, by energy resource, are shown in Table 6 for the world and the U.S. in selected years.[3,4] Analysis of the 1990 U.S. data yields the following specific carbon emission factors: coal, 2.30 TgC/GWy; oil, 1.99 TgC/GWy: gas, 1.37 TgC/GWy. These factors were used to estimate future U.S. emissions in Table 6. Higher factors were used to estimate future world emissions to fit the 1990 data for emissions from electricity generation.[4]

Energy projections that have been made by EIA and others, do not take into account limitations that might be imposed by carbon emission restrictions. In order to hold the 1990 values of carbon emission constant during the next century for electricity generation, it will be necessary to radically change the shares of electricity generation from those projected in Table 6.

In the U.S. it will be necessary to achieve over 46% nuclear plus renewable in 2020 and almost 58% in 2100 to hold the 1990 carbon emission level attributed to electricity generation. These values would rise two percentage points if the 1990 level, less 7%, were to be met. During the century it will also be necessary to eliminate the use of oil by 2025 and to reduce the coal share to less than 20% by 2075, or by 2050 to achieve the 7% lower than 1990 emission. The scenario proposed maintains a 25% share of electricity generation from gas.

On a world basis, the more rapid growth in projected energy use forces a more rapid reduction of fossil fuel electricity shares and requires a 70% and 80% reliance on nuclear and renewable energy by 2050 and 2100, respectively. In 2100, almost 20% of the electricity would be generated from gas, none from coal or oil. Further reduction in carbon emissions would require severe curtailment of coal and oil generating plants by 2050. Gas generation would be limited to less than 25% beginning in 2050.

The controversy over whether global warming is real or not should not be allowed to negate the many other beneficial attributes of renewable energy and nuclear

Table 6. Estimated shares of coal, oil, gas, and combined nuclear and renewable resources projected for electricity generation and the. indicated carbon emissions.

	U.S.			World		
	1990	2000	2020	1990	2000	2020
share, %						
coal	56	53	49	40	37	34
oil	4	3	1	10	10	9
gas	9	15	33	13	16	25
nuclear/renew.	31	29	18	37	37	32
emission, TgC						
indicated	477	565	835	1832	2200	3271
target (1990)			477			1832
target (1990-7%)			444			1704

Note: The target carbon emission values (1990 level or 7% lower) cannot be met by the projected approximate shares.

power. As has been stated by others[7] we cannot afford to take the risk that the effects of CO_2 in the atmosphere are of no concern. Accordingly, nuclear power development should be vigorously pursued in conjunction with hydroelectric, solar, and wind systems until it is clear what combination of options can meet emission goals during the coming century. No one option, by itself, is likely to meet the emission targets.

D. Nuclear Safety

Safety of nuclear reactors has an admirable record worldwide. The only serious accident (Chernobyl, 1986) occurred because of faulty design and improper operation. Even so, the effects of that accident have been and continue to be grossly overstated in many publications and much of the media. Health effects of the Chernobyl accident have been the subject of extensive study and a number of study results have been published. The accident resulted in a total of 31 immediate deaths. Three deaths resulted from non-radiological causes (explosion, fire, heart attack)[8]. Of the 231 patients hospitalized for acute radiation exposure, 28 deaths resulted. After 13 years of studies on the health effects of the accident, confirmed health effects remain elusive, according to the most recent French study.[9] There has been a high incidence of childhood leukemia and thyroid cancers, however the consequences of these have not been published.

Fast reactors have been designed to be passively safe and can provide electricity reliably and consistent with high environmental protection goals. Comparative risk/benefit analyses of competing technology options should be performed. It is important that in these analyses the complete systems are compared, including, for example the safety of coal mining and ash disposal risks on the one hand, and spent fuel treatment and radioactive waste risks on the other hand.

E. Nuclear Weapon Aspects

Nuclear weapon aspects of nuclear technology are perhaps the most serious public perception problem for nuclear power implementation. Quantification of the risks of materials being stolen or diverted from each point in the nuclear fuel cycle for use in a nuclear weapon should be made. These risks should be compared with other methods of building nuclear weapons, for example by covert mining and enriching uranium. Advancement of monitoring techniques and safeguards and their application by international bodies must be encouraged.

An inherent characteristic of a fast reactor system that operates at a conversion ratio of one and includes fuel recycling,[9] is its material diversion resistance. After initial startup of the reactor, no weapon-useful material is transported in or out of the reactor site. In the on-site fuel recycling facility, the processes used are such that attractive material does not exist in a pure form, nor in a non-highly radioactive form, and accountability of the material can be maintained to a high degree of accuracy. The discharged waste consists of fission products, with negligible traces of minor actinides. The incoming uranium can be natural, depleted, or separated from spent fuel from thermal reactors. Any of these types of uranium would require a substantial enrichment effort to produce weapon usable uranium. There are other, much simpler ways to obtain weapon-useable uranium. Thus, theft or diversion of this material for weapon use during transit to the reactor site would not be a likely event. Also these "simpler" ways could also be conducted in a covert manner much more easily.

F. System Design

System characteristics of a nuclear fuel cycle that facilitates the attainment of the directions set out above are those of a fast reactor system that operates with a conversion ratio near one, utilizes natural or depleted uranium as fuel, recycles its fuel material, and produces radioactive waste that contains no significant amount of actinides or long-lived fission products. This would make the siting of geologic repositories for disposal of unavoidable radioactive waste much easier, as repository performance would not have to be certified for thousands of years. Companion transmutation systems could be developed to further effect these objectives. Ideally, only fast reactors would be in use, thus avoiding the accumulation of spent fuel and enrichment tails inherent with thermal reactors, and eliminating the need for uranium mining for several centuries.

Much of the technology needed is available in the U.S. and internationally. Because the preferred fast reactor design probably would use metallic fuel and sodium as the coolant, both capable of high temperature operation, a high thermal efficiency, 38%, could be achieved.[10] Ways to further improve thermal efficiency should be investigated, for example through research and development of thermionic and thermoelectric direct conversion devices.

Other options that improve the once-through light water reactor system have been considered, and promising options should continue to be considered in the future. At present, the advanced fast reactor with fuel recycling appears to be the best option to deploy exclusively for electricity generation. The older concept of an infrastructure that utilized a fast reactor operating at a high breeding ratio to support fuel requirements for three or four thermal reactors that would use plutonium/uranium oxide fuel has not been favored in the U.S. Another concept, also an old one but more recently reintroduced, would utilize thorium as a fertile material and would rely on fission of U-233 to produce power. An advantage of the thorium system is that very little plutonium would be produced. Nevertheless, recently purified U-233 is a weapon-usable material. Another drawback is that there are probably less thorium resources in the U.S., if not in the world, than uranium.

G. Nuclear Power Applications

Applications for fast reactor systems may become more diverse in the next century. Ways to utilize the waste heat from the thermodynamic cycle should also be explored. In cold climates, district heating could be implemented in an environmentally beneficial way. Considerations for siting a passively safe fast reactor should be reevaluated to assess the viability of its location in populated areas for maximum application of waste heat.

Water desalination does not necessarily require high-temperature process heat, thus waste heat from a fast reactor principally producing electricity could be utilized for desalination. The expected shortage/high-cost/security of oil during the next century coupled with environmental concerns could result in a much greater demand for electricity for transportation. If the electricity for transportation were generated from fast reactor operation, significant reductions in carbon emissions could be made. Currently, carbon emissions from the transportation sector are about the same as from the electricity sector.

III. IMPLEMENTATION

Energy, and especially electricity generation is an appropriate area for federal government involvement, as there are a number of issues of national importance involved: safety, energy security, environmental impact, productivity, energy projections, and resource assessment. It seems essential, therefore to have an Energy Department at the national level.

This Energy Department, however, must differ significantly from the present Department of Energy. The new Energy Department should spend its authorized funds primarily on energy related activities. At present, the major share, 70%, of the Department of Energy's budget is spent on nuclear weapon programs. Not only are the departmental priorities reversed, the public perception of peaceful nuclear applications is undoubtedly, to some extent, jaundiced by the commonality of governmental administration of nuclear technology and the nuclear weapon program. The nuclear weapon program should be moved into a newly created Federal agency whose mission would be nuclear weapon development, design, production, and maintenance according to the need for these activities under national policies. The new agency should not be a part of the Defense Department, in keeping with the original Atomic Energy Act, and "Energy" should not be part of its name.

Before the creation of the Nuclear Regulatory Commission and the Environmental Protection Agency, the Atomic Energy Commission carried out the development and the demonstration of nuclear reactors in a responsible manner. There is a fallacy in the thesis that separate government entities are needed to administer laws dealing with regulation, environment, and technology. If one such organization can not be trusted to carry out the laws of the land, what is the rationale that two or three can do it better? The new Energy Department, proposed above, should be charged with enforcement of laws pertaining to the environment and to the safe operation of commercial energy enterprises, for example, nuclear reactors, nuclear fuel facilities, and waste repositories.

Similar attention should be given to the complete infrastructure for other than nuclear energy systems. Placing all energy activities, including their regulation, in a single department should permit an objective balanced effort on development and evaluation of energy systems, and projection of energy needs. A precise statement of the mission of the new Energy Department with measurable performance goals would insure accountable administration of the necessary regulatory programs.

IV. CONCLUSIONS

Projected energy growth over the next century indicates a quadrupling of world energy demand. Over the same period, U.S. energy demand, with already the highest per capita energy use rate, will continue to grow at about half the world rate. Fossil resources to satisfy the electricity sector share of primary energy requirements can be expected to be completely depleted toward the end of 2100. Of more importance, perhaps, although there is disagreement on its consequences, is the effect of carbon emissions on global warming if fossil resources continue to be used, even at current energy use levels.

A fast reactor system with fuel recycling can meet the total world electricity needs for about seven centuries. Used in conjunction with hydroelectric systems, together with wind and solar systems, when they become economically competitive, fast reactors can produce the world's electricity for over a millennium.

The fast reactor system with fuel recycling infrastructure appears to resolve issues dealing with radioactive waste disposal, carbon emissions, and energy resource depletion in a safe, environmentally acceptable, economically viable, and material diversion resistant manner.

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